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THE ANOMALOUS TRAJECTORIES OF THE PIONEER SPACECRAFT^a

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Because of their unique designs, the Pioneer 10 and 11 spacecraft have provided the cleanest Doppler, deep-space navigation data. Analysis of this data can be interpreted as showing an anomalous acceleration of these craft directed towards the Sun of $a_P \sim 8 \times 10^{-8} \text{ cm/s}^2$. The background of this discovery and the significance of the result are discussed.

1 Introduction

Some thirty years ago, on 2 March 1972, Pioneer 10 was launched on an Atlas/Centaur rocket from Cape Canaveral. Pioneer 10 was Earth's first space probe to reach an outer planet. After surviving intense radiation, on 4 December 1973 it successfully encountered Jupiter^{1–4}.

Today we are all used to spectacular photographs from the solar system. But in 1973 it was different. For those of us (speaker - MMN) who remember, the impact of the first Jupiter encounter photographs was astounding. To understand this one only has to compare the 25 January 1974 cover of *Science*¹ with the best Palomar telescope photographs.

Pioneer 10 was followed by Pioneer 11 (launched on 5 April 1973). After Jupiter and (for Pioneer 11) Saturn encounters, the two spacecraft have followed hyperbolic orbits near the plane of the ecliptic to opposite sides of the solar system. Pioneer 10 was also the first mission to “leave the solar system” when in June 1983 it passed beyond the orbit of Pluto³. (See Figure 1.)

The Pioneers have been amazingly robust. *They knew how to build cars in those days!* The Pioneers were adventures into the unknown, so great care was given to the design and reliability of the craft. Hence, although it was required (hoped) these craft would have a lifetime of 3 (7) years, they successfully oper-

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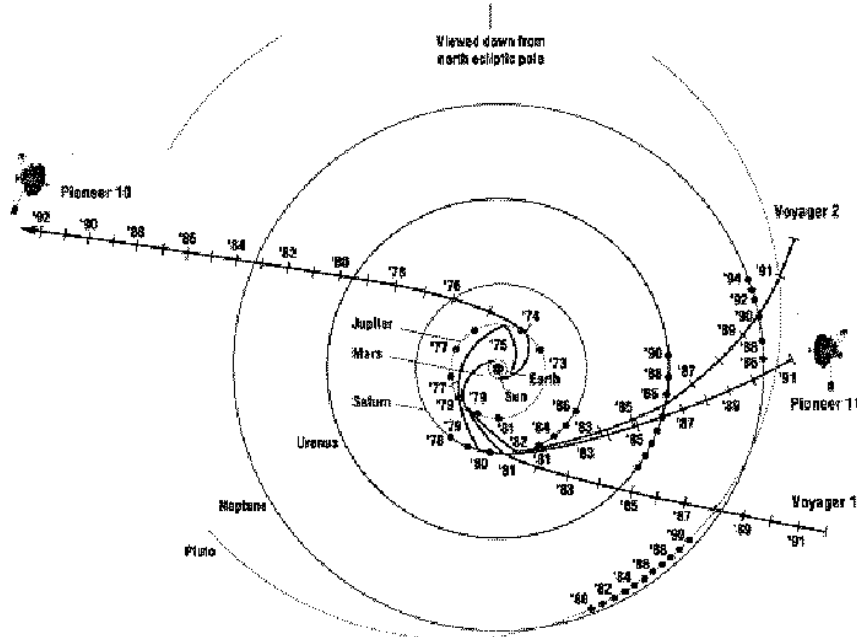


Figure 1: Ecliptic pole view of Pioneer 10, Pioneer 11, and Voyager trajectories. Pioneer 11 is traveling approximately in the direction of the Sun’s orbital motion about the galactic center. The galactic center is approximately in the direction of the top of the figure.

ated for much longer. Pioneer 10 (at a distance > 70 AU) is still transmitting and we have analyzed data up to 1998.5. The Pioneer 11 Doppler signals failed on 1 October 1990. So, after that date, when the spacecraft was ~ 30 AU away from the Sun, no useful data has been generated for our purposes.

2 Testing Newtonian Dynamics

I myself (MMN) became involved in this project while I was preparing a talk on antimatter and gravity for the 1994 Low Energy Antiproton conference ⁵. I wanted to argue that we really do not understand gravity at distances much larger than the size of the solar system. We know it is there, but we don’t know how well it obeys Newton/Einstein physics. Basically the rotation curves of spiral galaxies tell us something is wrong. Our “creationist” solution is dark matter (although we can’t find enough of it to explain the problem).

To better understand what spacecraft could tell us about this, I eventually was directed to John Anderson. He emailed me that rather than considering the orbits of three-axis stabilized craft like the Voyagers, spinning craft like the Pioneers were better since fewer maneuvers are necessary.

How you obtain a result from spacecraft is very simple to understand – in principle. You transmit an S-band signal to the craft via the Deep Space Network. It is transponded back and you compare the re-received signal to your station clocks. There will be a Doppler shift since the spacecraft is traveling out. From this shift you subtract out known effects, like the gravity of the Sun and any nearby planets.^b Then you see if any Doppler residuals are left over.

3 The Anomaly

As to what the Pioneers could actually tell us, John went on, “By the way, the biggest systematic in our acceleration residuals is a bias of 8×10^{-13} km/s² directed toward the Sun.” It turns out that indicative evidence of this had been around for some time. But the motivation to analyze it seriously had not arisen. Now it did⁶.

Our collaboration expended a great deal of effort in detailed analysis of the Pioneer 10 data between 1987.0 and 1998.5 and of the Pioneer 11 data between 1987.0 and 1990.75. When systematics had been considered, we obtained a present result of⁷ $a_P = (8.74 \pm 1.25) \times 10^{-8}$ cm/s².

4 A Standard Physic Explanation

Most people (including ourselves) believe the answer must be some systematic. But we have not found it. The most likely candidates are gas leaks from the thrusters or non-isotropic heat radiation. In what probably shows a deep respect for what they deal with, space navigators tend to think it is gas leaks and space scientists tend to think it is heat.

The navigators argue their case privately and the space scientists argue their case in print. The navigational and heat details are in our big report⁷. The ongoing heat discussions are in our references^{8–10}. You people will have to decide for yourselves, but we claim no “smoking gun” has been found.

The care of the design turned out to be beneficial to us. (See Figure 2.) The radioisotope thermoelectric generators (RTGs) were placed at the

^bI am sympathetic to the story Eric Adelberger told us about the commercial miscalibration of their micrometer. We spent a couple of months trying to understand evidence of an anomalously large corona signal. Eventually we realized that we needed to input physical parameters that had been determined elsewhere instead of using default operations of the codes.

The question probably must be settled by new experiment. A craft going quickly to deep space, built to minimize systematics, and with modern Doppler and range electronics is what is called for. We are thinking about this.

Acknowledgments

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